Systematic Design and Implementation of Decentralized Fuzzy-PD Controller for Robot Arm

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Abstract

Robot Motion control represents a major problem when developing efficient robotic control system. Linear motion controllers such as PD or PID are widely used for most of applications because they have straightforward structures and tuning procedures. It was approved that Fuzzy controllers highly enhance the control system performance but they require a complex or not systematic tuning and implementation. This paper introduces a systematic approach for developing efficient Fuzzy-PD controller for 3DOF robot arm. This approach is based on mapping a linear PD controller structure into nonlinear Fuzzy-PD structure. The approach is based on the mapping formulas developed by Jantzen. The Fuzzy PD experimental evaluation shows a high minimization of the tracking error for various applied trajectories.

Keywords

Robot Motion Control, Decentralized Robot Control, Fuzzy Controller

Introduction

The general structure of any robotic control system mainly involves two problems; trajectory planning and motion control. Trajectory planning objective is to estimate the optimum motion path for the robot and to avoid any existing obstacles. The objective of motion control is to precisely steer the robot to follow the optimum trajectory. Motion Control for robot manipulators use centralized approach or decentralized approach [Siciliano, Sciavicco, Villani, Oriolo]. In centralized control, the robot is actuated with direct drives (high-speed motors with no gear reduction) which cause the operational speed to rise to a point at which the inertial effects of the links cannot be negligible. The system behaves as multivariable system with *n* inputs (joint torques) and *n* outputs (joint positions) which interact by means of nonlinear relations. In decentralized control the manipulator is actuated by electric motors with reduction gears of high ratios.The presence of gears tends to linearizes the system dynamics.The system behaves as single input single output system and the coupling effects between joints due to varying configurations during motion are treated as disturbance inputs.

Decentralized approach involves using proportional – derivative controllers (PD) or proportional-integral derivatives controllers (PID) in closed loop systems. Example of earlier PID based robotic control systemswere developed by [Astroemand Haegglund] and [Bennett]. [Wen and Murphy] approved that PID controllers cannot guarantee global stability conditions when controlling robotic system. Further analysis of stability of PD and PID controllers can be found in [Siciliano et al.]. Santibañez et al. proposes a saturated nonlinear PID regulator for industrial robot manipulators. They apply an approach based on the singular perturbations method to analyze the exponential stability of the closed-loop system.

Recent researchs of fuzzy based motion control systems for robot was developed by[Ming Liu, Jin Yaochuand SadatiNasser]. Liu M. developed adaptive fuzzy controller and compare the response to a linear PD and cubic feedback control laws. The results showed that fuzzy control law achieves the best stability conditions. Jin Y. used a complex genetic algorithm GA for designing the fuzzy controller for decentralized control of robot manipulator. Sadati et al. proposed an adaptive fuzzy controller for robot manipulator. The algorithm allows the overall closed-loop system to be stabilized without having any prior knowledge of the robot dynamics.

Piltan et al. described an on-line tunable gain model free PID-like fuzzy controller for three degrees of freedom robot manipulator to reach the best performance. The main issue of using the

mathematical tunable gain method was to reduce the fuzzy logic controller limitations. Simulation results showed that the number of fuzzy rules could be significantly reduced using the proposed method. Kumar et al. compare the results obtained by PID and fuzzy controllers to control the 5DOF Lynx6 robot arm to reach the specified location with minimum error while meeting certain specification. The results showed that using fuzzy controller, a slight modification in the response of each individual motor for step input with various values of disturbances could be achieved.

The aim of this paper is to control the CRS CataLyst-5T robot arm using PD fuzzy controller. The performance of the proposed controller is investigated and compared with conventional PD controller. Two types of the reference trajectories are applied for the first three joint; namely sine trajectory and randomsteps trajectories.

Overview Of PD Fuzzy Controller

Fuzzy control FC is a control method based on fuzzy logic, which can be described simply as "control with sentences rather than equations"[Jantzen]. One of the most important advantages of fuzzy control is that it can be successfully applied to control nonlinear complex systems using operator experiences or control engineering knowledge without a mathematical model of the plant. The general structure a FC consititutes of three main stages: fuzzification, inference mechanism and defuzzification as shown in FIG 1.

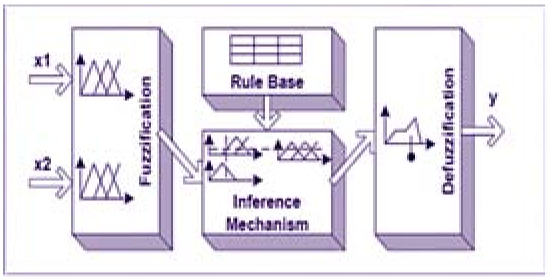

FIG. 1GENERAL STRUCTURE OF FUZZY CONTROLLERS

Implementation of an FLC requires the choice of three key factors: number of fuzzy sets that constitute linguistic variables, shape of membership functions and control protocol that determines the controller behavior. Thus, FLC can be tuned not just by adjusting controller parameters but also by changing control rules, membership functions etc. FLC is complex, nonlinear controller where rule base, inference mechanism and defuzzification methods are the sources of nonlinearities in FLC. However it's possible to construct a rule base with linear input-output characteristics.

A FPD controller is a fuzzified proportional-derivative (*PD*) controller. It acts on the same input signals, but the control strategy is formulated as fuzzy rules. The *FPD* controller has three gains, which are mainly for tuning the response, and they can also be used for scaling the input signal onto the input universe to exploit it better, where the crisp proportional derivative controller has only two gains which make it flexible and better. A typical structure of FPD controller is shown in FIG2. It has two inputs; the error signal '*e*' and the change of the error '*de/dt*'. The first input will be transformed from value '*e*' into the value '*E*' after multiplication with the error gain GE [Jantzen].

$$E = GE * e \tag{1}$$

By the same procedure, the second input will be transformed from value 'de/dt' ' into the value 'CE' after multiplication with the change of error gain GCE.

$$CE = GCE * \frac{de}{dt} \tag{2}$$

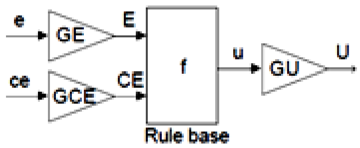

FIG. 2STRUCTURE OF PD FUZZY CONTROLLER

The two fuzzy inputs '*E*' and '*CE*' are processed by the rule base stage to produce the a new fuzzy variable 'u' which will be transformed into the value '*U*' after multiplication with the output gain *GU*.

$$U = GU * u \tag{3}$$

Although the controller needs both the error and the change of error as inputs, we will call it single-loop control, because in principle all three are formed from the error measurement (single feedback loop). The control signal *U(n)*, at the time instant *n*, is a nonlinear function of error and change in error.

$$U(n) = f(GE * e(n), GCE * \dot{e}(n)) * GU \tag{4}$$

As the function *f* is the rule base mapping, with two inputs and one output, the input-output mapping is a surface. A linear approximation of Equation (4) requires the following conditions [Namazov, Basturk]:

- Support sets of input linguistic variables must be large enough so that input values stay in limits.

- Linguistic values must consist of symmetric triangular fuzzy sets that intercept with neighboring sets at a membership value of so that for any time instant, membership values add to 1.
- Rule base must consist of and combinations of all fuzzy sets.
- Output linguistic variables must consist of fuzzy sets positioned at the sum of the peak positions of input fuzzy sets.
- The activation operator and should be multiplication and defuzzification method must be "*centre of gravity*" (*COG*).

This will result in

$$f(GE*e(n), GCE*\dot{e}(n)) \approx (GE*e(n)+GCE*\dot{e}(n)) \quad (5)$$

Inserting equation (5) into equation (4) yields the control action *U(n)*for the linear controller,

$$U(n) = (GE*e(n)+GCE*\dot{e}(n))*GU \quad (6)$$

$$= GE*GU*(e(n)+\frac{GCE}{GE}*\dot{e}(n))$$

The ideal continuous PD controller

$$u(n) = k_p\,(e(n)+T_d\,\frac{de(n)}{dt}) \quad (7)$$

where*u* is the controller output, *Kp* is the proportional gain, *e* is the error between the reference signal and the actual signal *y* and *Td* is the derivative time:

$$T_d = k_d / k_p \quad (8)$$

Comparing Equations (6) and (7), the gains are related as follows:

$$k_p = GE*GU \quad (9)$$

$$T_d = \frac{GCE}{GE}$$

$$k_d = GCE*GU$$

Experimental Work

In this work fuzzy PD controller is implemented using the CRS CataLyst-5T robot shown in FIG. 3. It is a 5 degree-of-freedom articulated robot mounted on a linear track. It has 5 joints powered by 5 DC motors and one linear track powered by one motor. Each DC motor has an electrical resistance of about 3.0 and a current - torque constant of 0.07 N.m/A. The rated voltage of the motor is 34 V and the PWM bus voltage is 35 V. Each joint of the robot has an incremental encoder to provide continuous information on motor position.

FIG. 3CRS CATALYST-5T ROBOT ARM

This robot comes with the CRS-C500 controller, which contains five PID feedback controllers operating about each motor and their structures cannot be modified. In order to implement our control strategy, we have to by-pass the CRS-C500 controller through the Quanser open-architecture mode which allows to use Simulink for real-time control implementation. In order to do so, a Quanser–MultiQ acquisition board is used together with a Quanser–Win-Con software (allowing to generate real-time code from Simulink). A switch mounted on the CRS-C500 control box allows us to switch back and forth from the Quanser-open-architecture mode to the CRS mode.

Implementaion of Fuzzy PDController

The controller objective is to precisely control the DC motor of each robot joints independently. The design procedure of fuzzy PD controller basedon linear PD controller is shown in FIG. 4.

The coupling gearboxes for all joints are identical (i.e. 72) , so that the dynamics of all joints may be approximated by applying the same controller structure for each joint. As the magnitude of the joints angle is at most 3.14 rad, the magnitude of the maximum error is 3.14 rad.Therefore the error gain will be equal to 3.14.The output gain will be equal to 1079 and finally the change of error gain will be equal to 95.

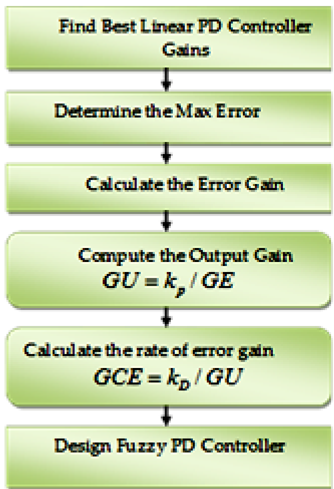

FIG. 4DESIGN PROCEDURE OF FUZZY PD CONTROLLER BASED ON LINEAR PD CONTROLLER

A scalling factor α can be used for both the input and the output gains as shown in FIG 5.Using scalling factor α equal to 0.097, will result in error gain of 0.3, rate of error gain of 9.5 and output gain of 103.

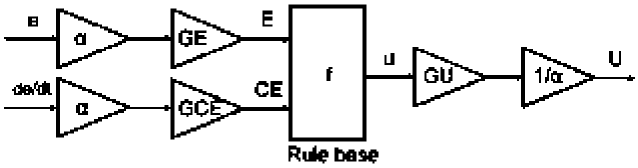

FIG. 5 STRUCTURE OF PD FUZZY CONTROLLER WITH SCALLING FACTOR

Implementation of fuzyy PD controller involves the following stages:

Fuzzification Stage

Fuzzification comprises the process of transforming crisp values into grades of membership for linguistic terms of fuzzy sets. The membership function is used to associate a grade to each linguistic term. The inputs of the FPD controller are the error signal and the change in error, and they are both mapped into three partition of fuzzy set, denoted by N(Negative), ZE(Zero),and P(Positive), respectively. For the first input 'error', trapezoidal membership function with three linguistic values are applied in the range of-0.3:0.3 as shown in FIG6. The equivalent gain of the error membership:

$$GE = output\ (1) / input\ (0.3) = 3.333$$

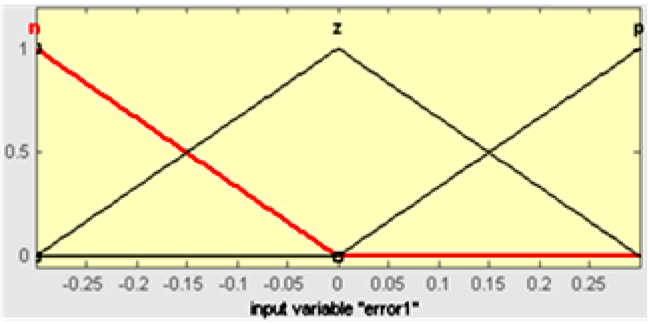

FIG. 6MEMBERSHIP FUNCTION FOR THE POSITIONING ERROR

For the second input 'rate of error', trapezoidal membership function with three linguistic values are applied in the range of -9.5:9.5 as shown in FIG.7 and therefore The equivalent gain of the change in error membership GCE=output (1)/ input (9.5) =0.105.

Fuzzy Rule Base

The collection of rules is called a rule base. The rules are in "*If….Then*" format and formally the *If* side is called the conditions and the *Then* side is called the conclusion. For example, the first rule states that:

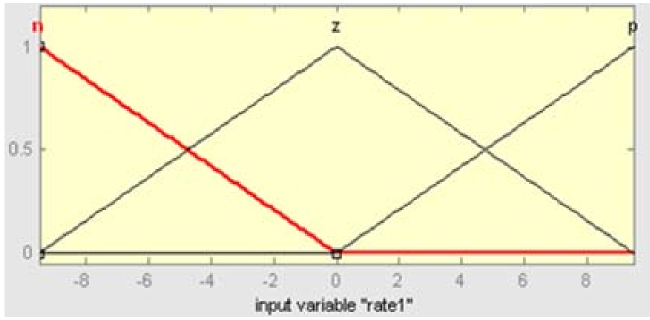

FIG. 7MEMBERSHIP FUNCTION FOR THE SECOND INPUT – RATE OF ERROR

If the error=LN and the error rate=LN *then* the change in control action = LN.

The program executes the rules and compute a control signal based on the measured inputs error (e) and change in error(de/dt). Fuzzy rules are dependent on the joints to be controlled and the type of the controller. These rules are determined from intuition or practical experience. In this paper, rules are designed based on the characteristics of robot DC motors. The fuzzified inputs are processed in the rule base stage. In this paper, since two inputs discourse are both divided into three fuzzy subsets, then there are total 9 fuzzy rules constructed.The number of fuzzy output linguistic values$N$, can be calculated according to:

$$N=2n-1 \tag{10}$$

where$n$ is number of input fuzzy subsets.

Thus the fuzzy output is mapped into five partition of fuzzy set. These are denoted by LN(Negative Large), N(Negative), ZE(Zero),and P(Positive), LP (Positive Large), respectively. In this paper, the MAX–MIN fuzzy composition method is used to obtain output from the inference rules. For a given specific input fuzzy set A' in U (input space), the output fuzzy set B' in O (output space) of the controller output is computed through the inference engine as following:

$$\mu_{B'}(\Delta u) = \max_{l=1}^{m}[\min(\mu_{A'}(e(n)), \mu_{A'}(\frac{d}{dt}e(n)))] \tag{11}$$

Defuzzification Stage

Defuzzification is the final stage of the fuzzy logic control. After the inference mechanism is finished, the defuzzification method converts the resulting fuzzy set into crisp values that can be sent to the joint as a control signal. FIG.8 shows the output membership, with five linguistic values (LN, N, Z, P, and LP) in the range of -103:103. The equivalent gain of the output membership GU=output (103)/ input (1) =103.

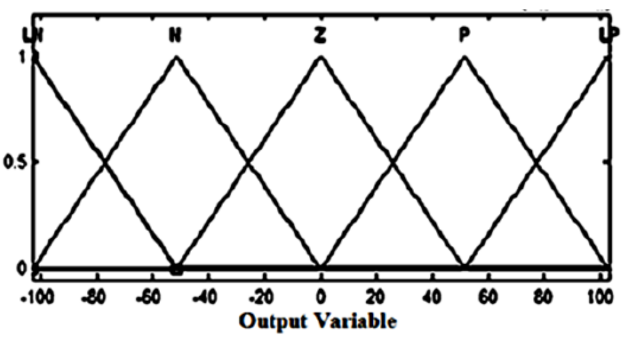

FIG. 8MEMBERSHIP OF THE OUTPUT DEFUZZIFICATION STAGE

The applied defuzzification technique is the center of gravity which describes the defuzzification output as following:

$$u_{defuzification} = \frac{\sum_i \mu_c(x_i)x_i}{\sum_i \mu_c(x_i)} \tag{12}$$

where x_i is a point in the universe U of the conclusion (i=1, 2, 3...) and its membership of the resulting conclusion set.

Results and Discussion

Two types of the reference trajectories are applied for the first three joint in order to make a comparison between linear PD controller (LPD) and Fuzzy PD controller (FPD); sine function and random steps trajectories. The sinsoidal trajectory is applied for the first three joints of CRS CataLyst-5T robot arm as shown in Figures 9-13. FIG. 9 shows the actual response of the first joint using PD and fuzzy PD controller. FIG. 10 shows that the linear PD controller of the first joint follows the reference trajectory with ± 1.7 deg error, while the fuzzy PD Controller follows the ref trajectory with -0.4 : 0.7 deg error.

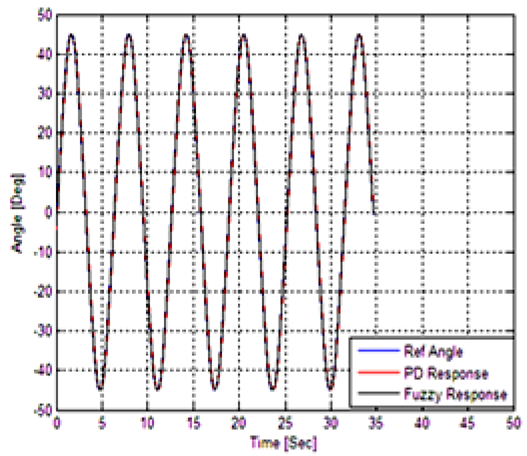

FIG. 9FIRST JOINT RESPONSE OF LPD AND FPD FOR SINE TRAJECTORY

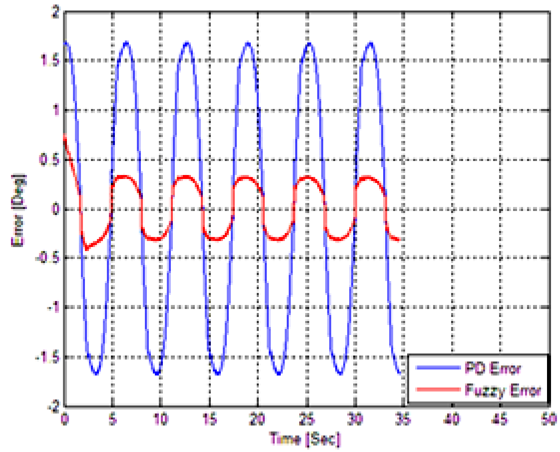

FIG. 10LPD AND FPD CORRESPONDING ERRORS OF FIRST JOINT

FIG. 11 shows the actual response of joint 2 using PD and fuzzy PD controller. FIG. 12 shows that the linear PD controller of the second joint follows the reference trajectory with - 0.9:0.55 degerror. A significant improvement in the trajectory is achieved using fuzzy PD. The figure shows that the fuzzy PD controller follows the refernce trajectory with - 0.3:0.2 degerror.

FIG 13 shows the errors of trajectory tracking of the third joint using the two conrollers.The results reveal that a good trcking could be achieved using fuzzy PD.The linear PD controller of the third joint follows the reference trajectory with - 0.9:0.7 degerror, where the fuzzy PD controller follows the trajectory with - 0.3:0.2 deg error.

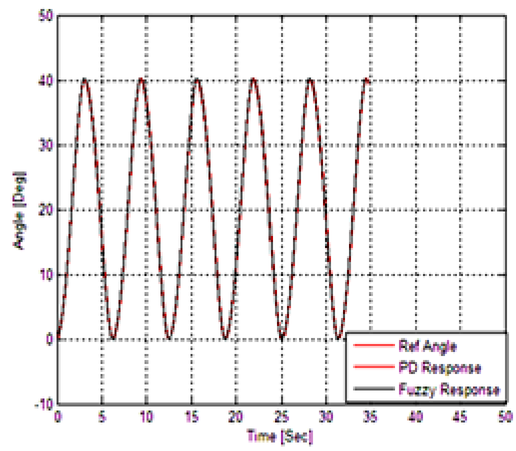

FIG. 11 SECOND JOINT RESPONSE OF LPD AND FPD FOR SINE TRAJECTORY

The random steps trajectoriesare applied for the first three joints of CRS CataLyst-5T robot arm are shown in Figures 14-15. FIG. 14 shows that the linear PD

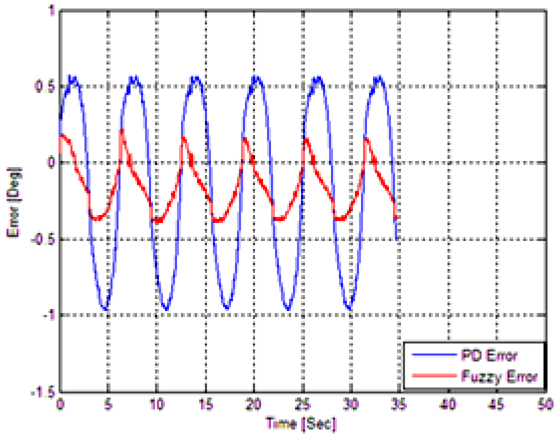

FIG. 12 LPD AND FPD CORRESPONDING ERRORS OF SECOND JOINT

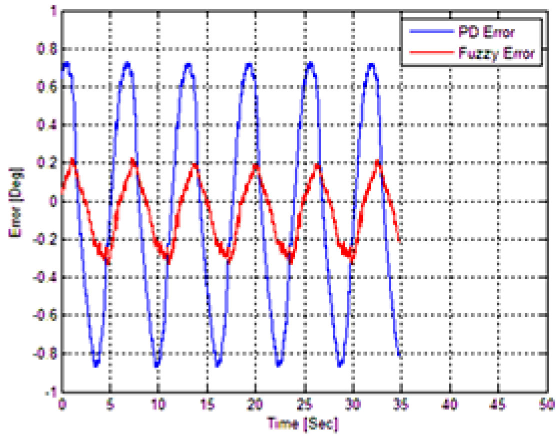

FIG. 13 LPD AND FPD CORRESPONDING ERRORS OF THIRD JOINT

controller of the first joint follows the ref trajectory with -1.25:0.9 deg error, where the fuzzy PD Controller follows the ref trajectory with ± 0.25 deg error.

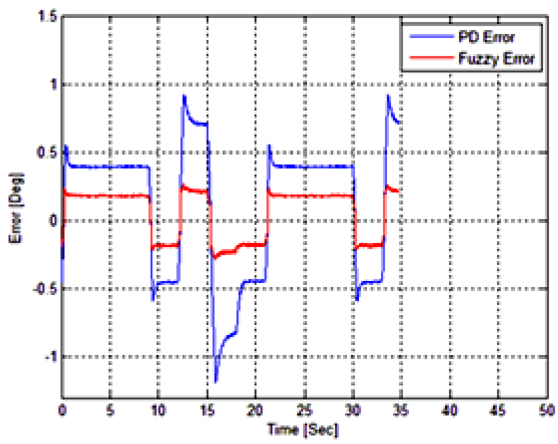

FIG. 14 TRACKING ERRORS OF THE FIRST JOINT (USING LPD AND FPD

Using the same reference trajectory for the second joint, FIG. 15 shows that the linear PD controller of the follows the trajectory with -1.25:0.9 deg error, where the fuzzy PD controller follows the reference trajectory with - 0.8:0.5 deg error, where the fuzzy PD controller follows the ref trajectory with - 0.4:0.25 degerror.

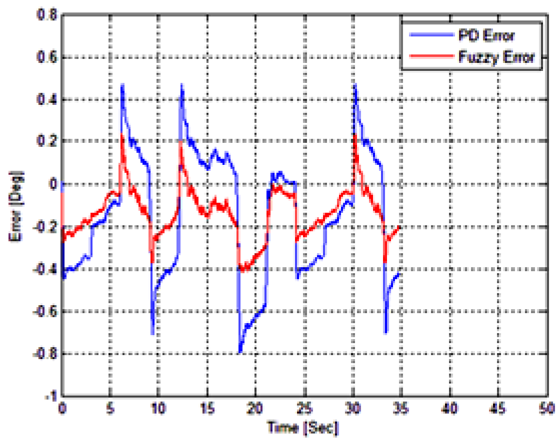

FIG. 15 TRCKING ERRORS OF THE SECOND JOINT USING LPD AND FPD

FIG. 16 shows that the linear PD controller of the third joint follows the reference trajectory with - 1.07:1.2 degerror, where the fuzzy PD Controller follows the trajectory with - 0.3:0.3 deg error.

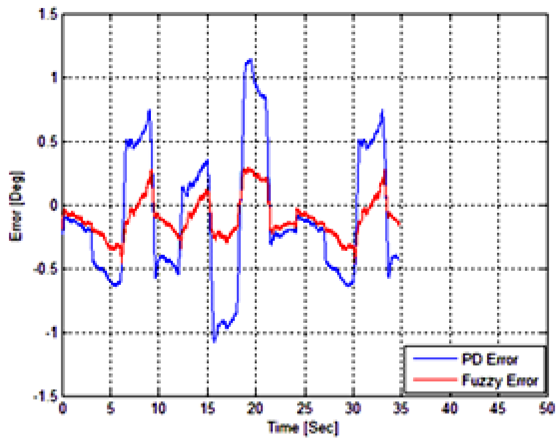

FIG. 16 LPD AND FPD CORRESPONDING ERRORS OF THIRD JOINT

Conclusions

In this paper an effective decentralized PD fuzzy logic controller for three degree of freedom articulated robot arm isinvestigated. The proposed decentralized control approach is successfully applied with minimum tracking error as a result of high gear ratios of robot joints. Upgrading from linear PD to Fuzzy PD control schemes leads to minimize the tracking error

by an average value of 60% for the two different trajectories. The experimental resultsindicate that the PD fuzzy controller can achieve good tracking to different references.Therefore it can applied to compensate the nonlinear dynamics resulting from joint-dependant inertia tensor and velocity coupling matrix. The controller is tested in two modes; offline and online. Offline test is implemented on an experimental dynamic model. Online implementation is performed on the real robot hardware. For both offline and online modes the control system is able to satisfy a robust and stable performance.

ACKNOWLEDGMENT

The lab facilities used in this work was supported by MEKATRON Tempus Project MEDA JEP-32050-2004.

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